

Methyl bromide alternatives in a bell pepper–squash rotation

T.M. Webster^{a,*}, A.S. Csinos^b, A.W. Johnson^c, C.C. Dowler^c, D.R. Sumner^b, R.L. Fery^d

^aUSDA-ARS, Crop Protection and Management Research Unit, Tifton, GA 31793-0748, USA

^bUniversity of Georgia, Department of Plant Pathology, Tifton, GA 31793-0748, USA

^cUSDA-ARS, Nematodes, Weeds, and Crops Research Unit, Tifton, GA 31793-0748, USA

^dUSDA-ARS, U.S. Vegetable Laboratory, Charleston, SC 29414-5334, USA

Received 22 November 2000; received in revised form 30 January 2001; accepted 1 February 2001

Abstract

Field studies were conducted to evaluate potential methyl bromide alternatives against multiple pests in a bell pepper (*Capsicum annuum* L.) – squash (*Cucurbita pepo* L.) cropping sequence. Early in the growing season, the most effective treatments in suppressing purple nutsedge (*Cyperus rotundus* L.) emergence through the polyethylene mulch were methyl bromide, methyl iodide, and chisel-injected 1,3-dichloropropene plus chloropicrin [1,3-D + C35 (chisel)]. However by the end of the season in 1999, only methyl bromide treatment had less purple nutsedge emerging through the polyethylene than the nontreated control. Each soil-applied treatment resulted in nematode-susceptible pepper plants with lower root-gall indices [*Meloidogyne* spp. (root knot nematode)] than the nontreated control, while there were no differences among treatments with the nematode-resistant pepper cultivar. Total fungi isolated from soil was lower in all treated plots relative to the nontreated control, with the exception of methyl iodide. However, methyl bromide was the only treatment that was consistently effective against *Pythium* spp. and *Fusarium* spp. A treatment of metham prior to planting squash was beneficial in reducing root-gall indices in plots treated with 1,3-D + C35 (chisel) and methyl bromide prior to the pepper crop. Methyl bromide, methyl iodide, and 1,3-D + C35 (chisel) applied before pepper resulted in squash with lower root-gall indices than the nontreated control. Glyphosate applied between the first and second crop eliminated exposed weed foliage through the polyethylene mulch, possibly muting the effects of the second crop treatment on weed densities. Results of this study indicate that there are some potential methyl bromide alternatives available to growers for use in pest control, however there does not appear to be one broad-spectrum pesticide that will replace methyl bromide. Also, an effective control for nutsedge species within the pepper–squash cropping system is still elusive. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: *Cyperus rotundus*; *Fusarium* spp; *Meloidogyne incognita*; Methyl bromide; *Pythium* spp; Metham; Methyl iodide; 1,3-dichloropropene

1. Introduction

Methyl bromide is an effective soil fumigant used extensively prior to planting many vegetable and fruit crops to control a broad-spectrum of pests that include nematodes, soilborne plant pathogenic fungi, soilborne insects, and weeds. Methyl bromide has been used since the 1950s to eliminate pest problems in many minor-use crops. Many of these crops have a limited number of pesticide alternatives due to the high cost associated with the registration of a pesticide. This high cost coupled with the relatively low numbers of hectares of these crops

makes most pesticide manufacturers reluctant to register pesticides for minor-use crops. While this has been an important issue surrounding minor-use crops, it has been tempered by the availability of methyl bromide and its biocide activities. However, methyl bromide was listed as a Class I ozone depleting substance by the US Environmental Protection Agency in 1993 and its use is scheduled to be halted by the year 2005. While methyl bromide is used for post-harvest pest control of stored products and for pest control of buildings and other structures, it is estimated that 85% of methyl bromide is used in agriculture as a preplant soil fumigant for high value vegetable and agronomic crops (Julian et al., 1998). With the impending elimination of this valuable compound, growers will need viable alternatives to manage a wide range of pests.

Previous research has identified several potential pest management alternatives for methyl bromide in various

* Corresponding author. Tel.: +1-229-386-3363; fax: +1-229-386-3437.

E-mail address: twebster@tifton.cpes.peachnet.edu (T.M. Webster).

cropping systems. Methyl iodide has been proposed as a methyl bromide replacement without the suspected depletion of the stratospheric ozone layer that is attributed to methyl bromide (Ohr et al., 1996). Becker et al. (1998) found that applications of methyl iodide at 168 kg/ha eliminated *Meloidogyne incognita* (Kofoed & White) Chitwood (southern root knot nematode) juveniles eight days after treatment and that root galling on lima beans [*Phaseolus lunatus* L. cv. Henderson] was suppressed to less than 1% at two months following treatment. Methyl iodide applied at rates as low as 28 kg/ha reduced populations of *M. incognita* to less than 3/100 cm³ of soil at five weeks after treatment in tomato (Noling and Gilreath, 1995). However, by 11 weeks after treatment the severity of root galls on tomato plants in the methyl iodide treatments was not different from the nontreated control. Laboratory studies indicated that methyl iodide was generally more biologically active on velvetleaf (*Abutilon theophrasti* Medik.) and Italian ryegrass (*Lolium multiflorum* Lam.) seeds than methyl bromide and optimum efficacy was related to soil hydration (Zhang et al., 1998).

Other potential methyl bromide replacements include metham, 1,3-dichloropropene, chloropicrin, and various combinations of these compounds. When applied in the fall of the year to nursery beds of bell pepper (*Capsicum annuum* L.), tomato (*Lycopersicon esculentus* Miller), and tobacco (*Nicotiana glauca* L.), metham efficacy was similar to methyl bromide plus chloropicrin (98:2) in 76 of 79 tested parameters which included crop vigor, winter annual weed control, soilborne fungal populations, nematode soil populations and nematode injury ratings (Csinos et al., 2000). In a transplant production system, the combination of metham + 1,3-dichloropropene + chloropicrin was similar to methyl bromide in control of weeds [yellow nutsedge (*Cyperus esculentus* L.), Florida pusley (*Richardia scabra* L.), and winter annual weed species], fungi (*Pythium* spp., *Rhizoctonia solani* Kühn), and crop response (stand count, crop vigor rating, and crop height) (Csinos et al., 1997). Other research found that plots treated with either 1,3-dichloropropene + chloropicrin or metham had lower tomato fruit yield, inferior control of yellow nutsedge, and higher fungal populations compared to the methyl bromide treated plots (Locascio et al., 1997).

The objective of this study was to determine the effects of soil chemical treatments on nematodes, weeds, soilborne plant pathogenic fungi, and crop response in a bell pepper–squash (*Cucurbita pepo* L.) cropping sequence in a plasticulture production system. In addition, bell pepper cultivars resistant or susceptible to *M. incognita* were used in the sequence across all soil treatments in order to evaluate the residual effects of the resistant crops in suppressing nematode populations in the subsequent *M. incognita*-susceptible squash crop.

2. Materials and methods

2.1. General

Field studies were conducted in 1998 and 1999 at the Coastal Plain Experiment Station in Tifton, GA. The soil was a Dothan loamy sand (fine-loamy, siliceous thermic Plinthic Paleudults: 93% sand, 4% silt, 3% clay) with 0.5% organic matter and a soil pH of 6.0 to 6.5. The area was naturally infested with *Meloidogyne incognita* [(Kofoed & White), Chitwood race 1, southern root knot nematode], *Pythium* spp., *Fusarium* spp., and purple nutsedge (*Cyperus rotundus* L.). The land was previously planted to cowpea [*Vigna unguiculata* (L.) Walp. cv. Pinkeye Purplehull] as a summer cover crop and hairy vetch (*Vicia villosa* Roth) as a winter cover crop to increase native densities of *M. incognita*.

The soil was disk harrowed and moldboard plowed 25–30 cm deep. Dolomitic limestone (2240 kg/ha) and 5–10–15 fertilizer (560 kg/ha) were broadcast and incorporated to a depth of 8–10 cm with a tractor-mounted rototiller. Single beds (76 cm wide, 7.6 m long, and 15 cm high) were established with a bed shaper. A single drip irrigation tube with emitters spaced 30 cm apart with a flow rate of 30 ml/min/30 m was placed in the center of the bed under the polyethylene mulch for application of water, fertilizer, and some fumigants. Black 32 µm-thick (1.25 mil) polyethylene mulch covered each bed immediately following chisel injected and soil fumigant applications. Designated treatments were applied through the drip irrigation system the following day.

Seedlings for transplants were grown in a greenhouse in plastic trays (6.4 cm × 34.3 cm × 67.3 cm) containing 128 cells (3.8 cm diameter by 6.4 cm deep). Cells were filled with a dry mixture of vermiculite and sphagnum peat moss (35:65). Trays were placed in a vat of water containing 20–20–20 fertilizer at 0.6 g/l of water. After 12 h, the medium in each cell contained the maximum moisture for seeding. The medium in each cell was compressed to a depth of 1.3 cm from the bottom of the tray. One seed was placed in each cell and covered with dry medium. Within 8 h the dry medium contained adequate moisture for seed germination. Trays remained in vats until after seed germination and were monitored for adequate moisture. To begin the acclimation of seedlings to field conditions, plants were removed from the greenhouse and placed in a field environment several days prior to transplanting.

2.2. Bell pepper

Treatments were arranged as a split-split-plot, with soil treatments applied prior to bell pepper (first crop) as the main plots, chemigated soil treatments applied through irrigation tubing prior to squash (second crop) as subplots (described later in detail in the squash

Table 1
Main and subplot treatments applied to pepper and squash crops

	Application method	Rate	Date applied
<i>Main plot (first crop treatments)^a</i>			
Fenamiphos + metham	Broadcast to soil surface ^b + chemigated through drip tape ^c	6.7 kg ai/ha + 240 kg ai/ha	30 March 1998; 31 March 1999
Methyl bromide	Fumigated	440 kg ai/ha	13 April 1998; 30 March 1999
Methyl iodide	Chemigated through drip tape ^c	440 kg ai/ha	13 April 1998; 1 April 1999
1,3-dichloropropene (1,3-D)	Chemigated through drip tape ^c	136 kg ai/ha	13 April 1998
1,3-dichloropropene + chloropicrin [1,3-D + C35 (chisel)]	Chisel injected	146 kg ai/ha + 83 kg ai/ha	13 April 1998; 30 March 1999
1,3-dichloropropene + chloropicrin [1,3-D + C35 (drip)]	Chemigated through drip tape ^c	146 kg ai/ha + 83 kg ai/ha	13 April 1998; 31 March 1999
Nontreated control	—	—	—
<i>Sub-plot (second crop treatments)^d</i>			
Metham	Chemigated through drip tape ^c	240 kg ai/ha	21 July 1998; 26 July 1999
Nontreated control	—	—	—

^aMain plots were 3.6 m × 7.6 m and treatments applied prior to pepper crop.

^bGranular fenamiphos was applied to the soil surface and shallowly incorporated.

^cPlots were chemigated for 60 min using a pump that delivered 126 ml/min. Water was added to each treatment to a total volume of 7500 ml. Following each 60 min treatment application, the lines were flushed with water for 30 min into the treated plots prior to application of the next treatment. This system was equipped with pressure regulators that maintained a consistent 83 kPa through the irrigation tubing.

^dSub-plots were 1.8 m × 7.6 m, each main plot treatment was divided to receive subplot treatments that were applied prior to squash crop.

section), and nematode-resistant and nematode-susceptible bell pepper cultivar were the sub-subplots (Table 1). Main plots were 3.6 m wide and 7.6 m long and consisted of two subplots each 1.8 m wide and 7.6 m long. The subplots were planted to two rows of bell pepper, one of each cultivar, which constituted the sub-subplot.

To allow for aeration prior to crop transplanting, two rows of holes 8 cm in diameter and spaced 30 cm apart were cut into the polyethylene mulch of each bed at 10 and 14 days after the methyl bromide treatment in 1998 and 1999, respectively. Five days after holes were cut in the polyethylene, a single greenhouse-grown pepper plant was planted in each hole with one row of *M. incognita*-resistant 'Charleston Belle' and one row of *M. incognita*-susceptible 'Camelot' pepper per bed on 27 April 1998 and 16 April 1999.

All pepper plots were sprayed on a 7–10-day schedule with 2 kg ai/ha maneb (Manex, Griffin LLC, Valdosta, GA 31601) and 1.3 kg ai/ha copper hydroxide (Kocide, Griffin LLC, Valdosta, GA 31601) in a water volume of 187 l/ha for foliar disease control. All plots received liquid fertilizer injected through the drip irrigation system once a week for a total of 130 kg/ha of nitrogen, 48 kg/ha of P₂O₅, 27 kg/ha K₂O, and 1 kg/ha boron.

Twenty soil cores (2.5 cm-diameter, 25 cm-depth) for nematode assay were collected from each row of pepper at monthly intervals from March through July in 1998 and April through July in 1999. The samples from each row within a plot were pooled and a 150 cm³ subsample was processed by centrifugal flotation method to separ-

ate nematodes from the soil (Jenkins, 1964). A 100 cm³ subsample was assayed for populations of *Pythium* spp. (P₅ARP media) (Jeffers and Martin, 1986), *Fusarium solani* (Mart.) Sacc. and *Fusarium oxysporum* Schlecht.:Fr. (modified PCNB) (Papavizas, 1967), *Aspergillus* spp., *Trichoderma* spp., *Penicillium* spp., and *Paecilomyces* spp. (OAES media) (Williams and Schmitthenner, 1960). Roots of five pepper plants from each plot were dug, washed in tap water, blotted dry with paper towels, and rated for root galls caused by *M. incognita* after final harvest. A scale ranging from 1 to 5 was used where 1 = 0%, 2 = 1% to 25%, 3 = 26% to 50%, 4 = 51% to 75%, 5 = 76% to 100% of the root system with galls.

The total number of living plants per plot was recorded in May of each year. Some plants began to show symptoms of wilting even in the presence of adequate soil moisture 4–6 weeks after planting in 1998. The number of wilted and healthy plants was recorded on 10 June 1998 and 10 July 1998.

All fruit were hand-harvested, separated into marketable and cull, counted, and weighed in late June and early July. After the final harvest, all weeds growing in the hole in the polyethylene where the bell peppers or squash plants were planted and those penetrating through the polyethylene mulch were identified and counted. Due to the diversity of weeds that emerged through the crop holes, weeds were divided into two categories: purple nutsedge and other weeds. The other weeds included bermudagrass [*Cynodon dactylon* (L.) Pers.], cutleaf

eveningprimrose (*Oenothera lacinata* Hill), Florida beggarweed [*Desmodium tortuosum* (Sw.) DC.], goosegrass [*Eleusine indica* (L.) Gaertn.], pink purslane (*Portulaca pilosa* L.), redroot pigweed (*Amaranthus retroflexus* L.), smallflower morningglory [*Jaquemontia tamnifolia* (L.) Griseb.], and Texas panicum (*Panicum texanum* Buckl.). After weeds were counted and identified, all pepper plants were cut at the soil surface and removed from the plots. All plots were sprayed with 2.2 kg ai/ha glyphosate to eliminate all existing weeds prior to applying treatments for the second crop.

2.3. Squash

Main plots (first crop soil treatments) were split into two treatments for the second crop. Subplots included a nontreated control and an application of metham chemigated through the irrigation tubing on 21 July 1998 and 26 July 1999 (Table 1). Squash cultivar 'Dixie' seedlings were produced in the greenhouse using the methods previously described. Seedlings were large enough to transplant 12–15 days after seeding and were transplanted in the holes between the original pepper plants on 5 August 1998 and 10 August 1999.

All plots of squash received liquid fertilizer through the drip irrigation system at three to four day intervals totaling 130 kg/ha of nitrogen, 57 kg/ha of P_2O_5 and 41 kg/ha K_2O over 12 applications. All squash plots were sprayed with 0.1 kg ai/ha mefenoxam and 1.6 kg ai/ha chlor-thalonil (Ridomil Gold Bravo, Novartis Crop Protection, Inc., Greensboro, NC 27419) for control of crown and foliar diseases and 0.11 kg ai/ha permethrin (Pounce, FMC Corporation, Agricultural Products Group, Philadelphia, PA 19103) and 4.61 ai/ha potassium salts of fatty acids (M-Pede, Mycogen Corporation, San Diego, CA 92121) for insect control on a 7–10 day interval.

Five squash plants were dug from each plot following the last harvest and rated for galls as previously described for pepper. Squash fruit were harvested three times a week for 2–3 weeks. Fruit were graded as either marketable or cull, and the number and weight at each harvest were determined. After the final harvest, weed populations were determined and root galls were rated from five plants as previously described.

2.4. Data analysis

All data were subjected to analysis of variance and means separated using Fisher's Protected LSD Test or Duncan's Multiple Range Test, both at an alpha level of 0.05. Prior to analysis of variance, data on pest populations were square-root-transformed, as necessary. Mean separation used transformed data, but the original data presented for clarity.

3. Results and discussion

3.1. Bell pepper

There were no differences among soil treatments in the number of root galls found on 'Camelot' pepper, a cultivar susceptible to *M. incognita*, in 1998, though all treatments had fewer root galls than the nontreated control (Table 2). Similarly, all treatments to 'Camelot' resulted in fewer root galls than the nontreated control in 1999, however methyl bromide, methyl iodide, and 1,3-D + C35 (chisel) also had lower root-gall indices than fenamiphos + metham and 1,3-D + C35 (drip) (Table 3). There were no differences among treatments or the nontreated control in root-gall indices for 'Charleston Belle' pepper, a cultivar resistant to *M. incognita*, in 1998 or 1999 (Tables 2 and 3).

Differences in nematode populations in the soil could not be detected in 1998 (data not shown), however there were differences among treatments in 1999. Soil samples collected within the row of 'Camelot' pepper indicated that all soil treatments suppressed *M. incognita* populations relative to the nontreated control (Table 3). All treatments, except methyl bromide, had lower *M. incognita* populations than the nontreated control in the 'Charleston Belle' pepper. However, the number of *M. incognita* recovered from the nontreated soil of 'Charleston Belle' pepper was approximately one-ninth of the population recovered from the nontreated soil of 'Camelot' pepper.

Both bell pepper cultivars had low populations of *Paratrichodorus minor* (Colbran) Siddiqi (stubby-root nematode) in the nontreated control in 1999 (Table 3). Higher populations were found in the fenamiphos + metham treatments in both pepper cultivars and in 'Camelot' pepper methyl bromide and 1,3-D + C35 (chisel) treatments than in the nontreated control. Densities of a third nematode species, *Helicotylenchus dihystera* (Cobb) Sher. (spiral nematode), were suppressed by all treatments relative to the nontreated control, with the exception of fenamiphos + metham in the soil of the 'Charleston Belle' pepper. Previous research in a container system indicated that on a molar basis methyl iodide was more efficacious than methyl bromide against three plant-parasitic nematodes, including *M. incognita* (Becker et al., 1998). With the exception of the number of *Paratrichodorus minor* recovered from soil in which 'Camelot' pepper was grown (Table 3), differences in nematode response between methyl bromide and methyl iodide treatments could not be detected.

Purple nutsedge pierced the polyethylene mulch barrier and became the principle weed in these studies. At the conclusion of the season in 1998, only the methyl bromide and 1,3-D + C35 (chisel) treatments had lower purple nutsedge shoot densities piercing the polyethylene mulch relative to the nontreated control (Table 2). These treatments, in addition to methyl iodide, suppressed

Table 2

The effect of soil treatment and crop cultivar on pest populations in pepper in 1998^a

Treatment	Root-gall index ^b		Weed densities		
	'Camelot'	'Charleston Belle'	Through polyethylene	Through crop hole	
			Purple nutsedge ^c	Purple nutsedge	Other weeds ^d
			no. per plot		
1,3-D (drip)	1.13 b	1.06 a	23 ab	5 ab	40 a
1,3-D + C35 (chisel)	1.13 b	1.00 a	2 b	1 ab	3 c
1,3-D + C35 (drip)	1.19 b	1.19 a	40 ab	8 ab	36 a
Methyl bromide	1.31 b	1.13 a	0 b	0 b	3 c
Methyl iodide	1.50 b	1.19 a	12 ab	1 ab	16 b
Nontreated control	2.31 a	1.06 a	64 a	10 a	45 a

^aTreatment means were separated using Duncan's multiple range test ($P = 0.05$). Differences among treatments with the same letter within a column could not be detected.

^b*Meloidogyne incognita* (southern root knot nematode) root-gall index was rated on a scale of 1–5 (1 = 0%, 2 = 1% to 25%, 3 = 26% to 50%, 4 = 51% to 75%, 5 = 76% to 100% roots galled at the conclusion of the season).

^cPurple nutsedge (*Cyperus rotundus* L.).

^dOther weeds included bermudagrass [*Cynodon dactylon* (L.) Pers.], cutleafevening primrose (*Oenothera laciniata* Hill), Florida beggarweed [*Desmodium tortuosum* (Sw.) DC.], goosegrass [*Eleusine indica* (L.) Gaertn.], pink purslane (*Portulaca pilosa* L.), redroot pigweed (*Amaranthus retroflexus* L.), smallflower morningglory [*Jaquemontia tamnifolia* (L.) Griseb.], and Texas panicum (*Panicum texanum* Buckl.).

Table 3

The effect of soil applied treatments on nematode populations and incidence of root galling in pepper in 1999^a

Treatment	<i>Meloidogyne incognita</i> ^b		<i>Paratrichodorous minor</i>		<i>Helicotylenchus dihystrera</i>		Root-gall index ^c	
	'Camelot'	'Charleston Belle'	'Camelot'	'Charleston Belle'	'Camelot'	'Charleston Belle'	'Camelot'	'Charleston Belle'
	no. per 150 cm ³ of soil							
1,3-D + C35 (chisel)	9 b	4 b	74 ab	45 ab	0 b	0 b	1.0 c	1.0
1,3-D + C35 (drip)	108 b	15 b	40 b–d	51 ab	0 b	3 b	1.3 b	1.0
Fenamiphos	219 b	4 b	53 bc	71 a	4 b	9 ab	1.3 b	1.0
+ metham								
Methyl bromide	5 b	54 ab	100 a	49 ab	0 b	3 b	1.0 c	1.0
Methyl iodide	4 b	3 b	33 cd	34 ab	0 b	0 b	1.0 c	1.0
Nontreated control	960 a	109 a	10 d	29 b	38 a	23 a	1.7 a	1.0

^aTreatment means were separated using Duncan's multiple range test ($P = 0.05$). Differences among treatments with the same letter within a column could not be detected.

^b*Meloidogyne incognita* (southern root knot nematode), *Paratrichodorous minor* (stubby-root nematode), *Helicotylenchus dihystrera* (spiral nematode).

^c*Meloidogyne incognita* root-gall index was rated on a scale of 1–5 (1 = 0%, 2 = 1% to 25%, 3 = 26% to 50%, 4 = 51% to 75%, 5 = 76% to 100% roots galled at the conclusion of the season).

purple nutsedge emergence through the polyethylene mulch in the early season of 1999 (Fig. 1). However, methyl iodide and 1,3-D + C35 (chisel) only suppressed purple nutsedge emergence and growth early in the season; by the conclusion of the season in 1999, only methyl bromide had lower purple nutsedge shoot densities than the nontreated control. These results indicate that in terms of nutsedge control, an effective replacement for methyl bromide has not yet been identified. However, some of these treatments may be a component of a future nutsedge management system.

Weeds also emerged through the holes in the polyethylene cut for the crop transplants. Compared to the nontreated control, only methyl bromide reduced the number of purple nutsedge that emerged through the crop holes (Table 2). Other weeds were suppressed, relative to the nontreated control, by methyl bromide, methyl iodide and 1,3-D + C35 (chisel) in 1998 (Table 2) and by all treatments in 1999 (data not shown). The number of weeds emerging through the crop holes in the polyethylene was 55 and 20 plants in the nontreated plots in 1998 and 1999, respectively. However, the total area of

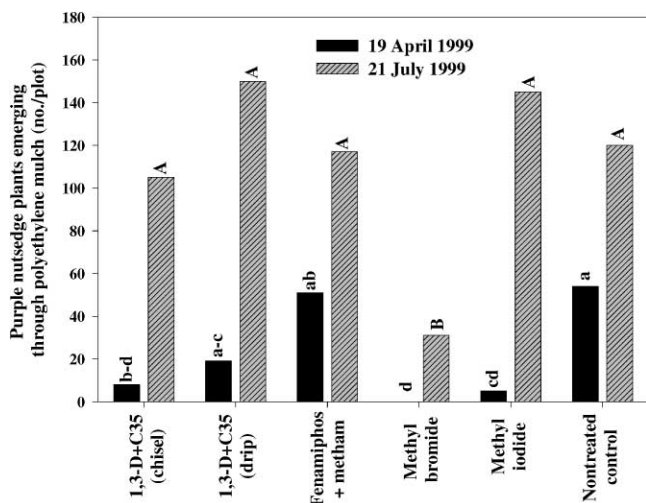


Fig. 1. The effect of soil applied treatments on purple nutsedge densities in pepper in 1999. Treatment means were separated using Fisher's Protected LSD at an alpha level of 0.05. Data were square root transformed prior to analysis and treatment means separated in this form, but presented in their original form in this figure. Treatment means from the early rating data were separated using lowercase letters, while those from the later data were separated using capital letters.

bare soil exposed in each bed by the holes cut into the polyethylene was less than 1.3% ($< 0.25 \text{ m}^2$) of the total area of each bed. Without the polyethylene mulch covering the majority of the bed, it is likely that weed densities would have been much higher and would have greatly affected crop production. While polyethylene mulch can be used to suppress weeds that are unable to penetrate the layer, it can also be an important management tool for nutsedges. Research has indicated that various polyethylene mulches suppressed nutsedge shoot emergence, tuber viability, and altered the competitive relation between nutsedge and crop (Chase et al., 1998; Majek and Neary, 1991; Patterson, 1998).

Pepper plants of both cultivars began to wilt and die in approximately three to four weeks after transplanting in 1998 with a differential mortality rate among treatments. The major pathogenic fungi isolated from the roots of dying plants were *Pythium* spp. [primarily *P. aphenidermatum* Edson (Fitzp.)]. The nontreated control, 1,3-D (drip), and 1,3-D + C35 (drip) treatments had the most wilted plants with no differences between bell pepper cultivars (Table 4). Methyl iodide, methyl bromide, and 1,3-D + C35 (chisel) treatments reduced the number of wilted plants. Differences in plant wilting among treatments could not be detected in 1999. Total fungi isolated from soil were lower in all treated plots relative to the nontreated control, with the exception of methyl iodide, which had almost twice as many colony forming units of fungi as any other treatment (Table 5). This same trend was observed with *Penicillium* spp. and *Paecilomyces* spp. Methyl bromide had the lowest total number of fungi

Table 4

Pepper plant health and cumulative crop yield in 1998

Treatment	Wilted plants ^{a,b}		Crop yield ^a	
	'Camelot'	'Charleston Belle'	'Camelot'	'Charleston Belle'
	%		kg per plot	
1,3-D (drip)	78 a	88 a	1.94 c	0.40 c
1,3-D + C35 (chisel)	12 d	32 b	11.7 a	6.35 b
1,3-D + C35 (drip)	63 ab	78 a	2.19 c	0.48 c
Methyl bromide	22 cd	32 b	7.81 b	10.46 a
Methyl iodide	42 bc	37 b	2.86 c	3.16 c
Nontreated control	81 a	94 a	0.54 c	0.45 c

^aTreatment means were separated using Duncan's multiple range test ($P = 0.05$). Differences among treatments with the same letter within a column could not be detected.

^bPepper plants of both *Meloidogyne incognita*-susceptible ('Camelot') and *M. incognita*-resistant ('Charleston Belle') varieties began to wilt and die in approximately three to four weeks after transplanting in 1998 with a differential mortality rate among treatments. Major pathogenic fungi isolated from the roots of dying plants were *Pythium* spp. (primarily *P. aphenidermatum*).

and was the only treatment that was consistently effective in suppressing fungi across all species evaluated (*Pythium* spp., *Fusarium solani*, total *Fusarium* spp., *Trichoderma* spp., *Penicillium* spp., and *Paecilomyces* spp.). Fenamiphos + metham controlled some of the pathogenic fungi, but did not reduce *Fusarium* spp. Both 1,3-D + C35 (chisel) and (drip) did not reduce populations of the beneficial *Trichoderma* spp. and were effective in reducing *Penicillium* spp., *Paecilomyces* spp. and total fungi relative to the nontreated control. However, both treatments had similar populations of *Fusarium solani* and *Pythium* spp. to that of the nontreated control (Table 5).

Fruit yield (kg per plot) of pepper in 1998 was highest with 1,3-D + C35 (chisel) and methyl bromide for 'Camelot' and 'Charleston Belle' cultivars, respectively (Table 4). Differences in fruit yield could not be detected among the nontreated control, methyl iodide, 1,3-D + C35 (drip), and 1,3-D (drip) in either cultivar in 1998. Lower yields from these treatments were probably related to the *Pythium* spp. that caused significant plant wilting and mortality. In 1999, only 1,3-D + C35 (chisel) increased yield above the nontreated control for both 'Charleston Belle' and 'Camelot' cultivars. Fenamiphos + metham and methyl bromide treatments had higher fruit yields than the nontreated controls for 'Charleston Belle' pepper (Fig. 2). However, there were similar fruit yields among 1,3-D + C35 (chisel), 1,3-D + C35 (drip), and methyl bromide for both cultivars, and fenamiphos + metham for 'Charleston Belle', and methyl iodide for 'Camelot' pepper.

Table 5
The effect of soil applied treatments on fungal populations in pepper^a

Treatment	<i>Pythium</i> spp.	<i>Fusarium solani</i>	Total <i>Fusarium</i> spp.	<i>Trichoderma</i> spp. (× 1000)	<i>Penicillium</i> spp. + <i>Paecilomyces</i> spp. (× 1000)	Total fungi (× 1000)
	CFU ^b					
1,3-D + C35 (chisel)	29 cd	420 b	760 bc	75.1 a	0 d	93.5 c
1,3-D + C35 (drip)	109 ab	370 b	880 b	77.5 a	0 d	111.4 b
Fenamiphos + metham	63 bc	1750 b	2450 a	5.3 b	8.2 bc	66.4 c
Methyl bromide	1 d	20 c	120 c	1.5 b	4.4 c	36.3 d
Methyl iodide	257 a	8610 a	9970 a	22.3 a	25.7 ab	213.7 a
Nontreated control	237 ab	970 ab	2400 a	24.2 a	76.7 a	304.9 a

^aTreatment means were separated using Duncan's multiple range test ($P = 0.05$). Differences among treatments with the same letter within a column could not be detected.

^bNumber of colony forming units (CFU) per gram of oven-dry soil.

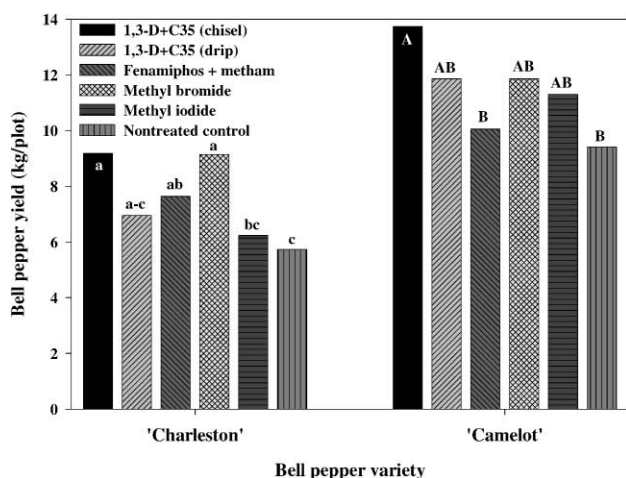


Fig. 2. The effect of soil treatment on pepper yield for both *Meloidogyne incognita*-resistant and *M. incognita*-susceptible pepper varieties in 1999. Treatment means were separated using Fisher's Protected LSD at an alpha level of 0.05; lower case letters were used to differentiate treatments in *M. incognita*-resistant pepper, while capital letters were used to separate treatment means in *M. incognita*-susceptible pepper.

3.2. Squash

Relative to all other treatments, a higher population of *M. incognita* was detected following the first crop treatment of 1,3-D + C35 (chisel) in 'Camelot' pepper that were left nontreated prior to the squash crop in 1998 (Table 6). Differences in *M. incognita* populations could not be detected among all other treatments and the nontreated control for the first crop followed by nontreated control for the second crop in 1998. There were significant differences in number of *M. incognita* recovered from soil among first crop soil treatments in

1999 (Table 7). Treatments of methyl bromide, 1,3-D + C35 (chisel), and fenamiphos + metham applied prior to the first crop resulted in lower *M. incognita* populations than in the nontreated control. There was a significant second crop treatment by pepper cultivar interaction in 1999, which indicated that a treatment of metham applied through the irrigation tubing following the susceptible cultivar of pepper ('Camelot') had lower *M. incognita* soil populations than did the same cultivar that did not have any application for the control of nematodes prior to the second crop. In plots that had resistant pepper cultivar as the first crop, there were no differences in *M. incognita* soil populations between second crop treatments of metham and nontreated plots (Table 7). Previous research indicated that cucumber following nematode-resistant tomato had lower soil populations of *M. incognita* than those following nematode-susceptible tomato (Hanna et al., 1994). Clearly pest resistant cultivars, where possible, should be one component of a methyl bromide alternative system.

Root-gall indices of squash in 1998 indicated no differences among first crop or second crop treatments when squash was planted following the nematode-resistant pepper cultivar ('Charleston Belle') (Table 6). However, there were differences among treatments following the nematode-susceptible cultivar ('Camelot') in 1998. Squash in plots that were treated with methyl bromide (first crop) followed by a nontreated control (second crop) or 1,3-D + C35 (chisel) (first crop) followed by nontreated control (second crop) both had higher root-gall indices than the nontreated control for the first crop followed by nontreated control for the second crop treatment. However, when an application of metham was applied through the drip irrigation tubing prior to the

Table 6

The effect of first and second crop treatments on *Meloidogyne incognita* (southern root knot nematode) population and root-gall indices in the second crop of squash in 1998^a

First crop Treatment	Second crop Treatment	<i>Meloidognye incognita</i>		Root-gall index ^c	
		‘Camelot’ ^b	‘Charleston Belle’	‘Camelot’	‘Charleston Belle’
————no. per 150 cm ³ of soil————					
1,3-D (drip)	Metham	5 b	0 b	1.1 c	1.1 c
	Nontreated control	10 b	8 b	1.0 c	1.0 c
1,3-D + C35 (chisel)	Metham	3 b	3 b	1.0 c	1.0 c
	Nontreated control	50 a	8 b	2.2 a	1.3 bc
1,3-D + C35 (drip)	Metham	0 b	0 b	1.1 c	1.0 c
	Nontreated control	10 b	3 b	1.2 bc	1.1 c
Methyl bromide	Metham	5 b	3 b	1.2 c	1.0 c
	Nontreated control	0 b	0 b	1.8 ab	1.0 c
Methyl iodide	Metham	0 b	0 b	1.2 bc	1.0 c
	Nontreated control	0 b	0 b	1.2 bc	1.0 c
Nontreated control	Metham	3 b	0 b	1.0 c	1.0 c
	Nontreated control	8 b	8 b	1.1 c	1.0 c

^aTreatment means were separated using Duncan's multiple range test ($P = 0.05$). Differences among treatments with the same letter could not be detected.

^bFirst crop treatments included a *M. incognita*-susceptible pepper ('Camelot') and a *M. incognita*-resistant pepper ('Charleston Belle').

^c*Meloidogyne incognita* root-gall index was rated on a scale of 1–5 (1 = 0%, 2 = 1% to 25%, 3 = 26% to 50%, 4 = 51% to 75%, 5 = 76% to 100% roots galled at the conclusion of the season).

Table 7

The effect first crop (pepper) treatments on second crop (squash) nematode population, root-gall index, and crop response in 1999^a

Treatment	<i>Meloidogyne incognita</i> (no./150 cm ³ soil)	Root-gall index ^b	Plant vigor rating ^c	Fruit weight (kg/plot)	Marketable Fruit ^d (%)
1,3-D + C35 (chisel)	9 bc	1.1 b	4.1 b	1.1 b	60 ab
1,3-D + C35 (drip)	26 a–c	1.6 a	5.1 ab	1.0 b	52 b
Fenamiphos + metham	10 bc	1.5 ab	4.4 b	0.9 b	48 b
Methyl bromide	1 c	1.0 b	6.5 a	2.7 a	74 a
Methyl iodide	35 a–c	1.1 b	4.6 ab	1.6 b	74 a
Nontreated control	84 a	1.8 a	4.4 b	1.0 b	55 ab
Interactions					
Metham – 'Camelot'	1 b	1.3	4.9	1.5	58
Metham – 'Charleston Belle'	12 ab	1.2	4.9	1.6	65
Nontreated control – 'Camelot'	73 a	1.7	4.8	1.2	61
Nontreated control – 'Charleston Belle'	24 ab	1.2	4.8	1.2	60

^aTreatment means were separated using Duncan's multiple range test ($P = 0.05$). Differences among treatments with the same letter within a column above the centerline or in interaction below the center line, could not be detected.

^b*Meloidogyne incognita* root-gall index was rated on a scale of 1–5 (1 = 0%, 2 = 1% to 25%, 3 = 26% to 50%, 4 = 51% to 75%, 5 = 76% to 100% roots galled at the conclusion of the season).

^cPlant vigor was rated on a scale of 1 (least vigorous) to 10 (most vigorous).

^dMarketable fruit were the percentage of the total harvested squash that were not graded as a cull.

second crop, the root-gall indices in all first crop treatments did not exceed a value of 1.2 in 1998 (Table 6).

Root-galls indices in squash in 1999 caused by *M. incognita* indicated that there was no effect of the second crop treatments. However, there was an effect of the first crop soil treatments on the second crop root-gall indices (Table 7). Methyl bromide, methyl iodide, and 1,3-D + C35 (chisel) had lower root-gall indices than the

nontreated control. Fenamiphos + metham and 1,3-D + C35 (drip) were not different from the nontreated control. While there was no significant interaction among pepper cultivars and second crop applications in root gall ratings, the trend in root-gall indices reflected the numbers of *M. incognita* in the soil (Table 7).

Squash plant vigor was influenced by the first crop treatments and was greatest in methyl bromide treated

plots (Table 7). All other treatments were not different from the nontreated control. Differences in plant vigor could not be detected among second crop treatments nor related to the cultivar of the previous pepper crop. Higher plant vigor ratings from the methyl bromide treatment resulted in higher squash yields relative to all other treatments in 1999 (Table 7). The nontreated control was similar in yield to all other nonmethyl bromide treatments. Differences in crop yield in 1998 among treatments could not be detected (data not shown). Approximately 74% of the harvested fruit were marketable from the methyl bromide and methyl iodide plots in 1999, but this was not different from the nontreated control (Table 7). These values were higher than those from plots treated with 1,3-D + C35 (drip) and fenamiphos + metham. Second crop treatments did not have any detectable effect on plant vigor rating, fruit weight, or the percent of marketable fruit (Table 7).

Nutsedges were identified as the most troublesome weeds of vegetable crops in Georgia (Webster and MacDonald, unpublished). While purple nutsedge was a problem during the first crop, the presence of this weed species was erratic in the second crop. Differences in purple nutsedge densities among treatments could not be detected in the second crop in 1998 or 1999, nor could any trends within the data be observed (data not shown). Treatment of the plots between the first and second crop with glyphosate probably had a significant influence on the reduction of purple nutsedge shoots in the second crop. With the exception of the methyl bromide treatments, all plots had purple nutsedge shoot densities greater than 5/m² emerged through the polyethylene and measured 25–61 cm in height at the time of glyphosate treatment. This application of glyphosate reduced the purple nutsedge shoot population in the second crop 82–99%, regardless of the second crop treatment. The nonselective herbicide paraquat is often used to eliminate weedy vegetation between vegetable crops, primarily because of its low price, quick action, and broad spectrum of weed control. However, this will often only provide contact burn of exposed purple nutsedge foliage and will not control any underground tubers. Glyphosate was reported to control nutsedge tubers that were attached to treated foliage (Doll and Piedrahita, 1982). These researchers found that new shoots of purple nutsedge that emerged following glyphosate applications originated from dormant tubers. Based on the reduced nutsedge populations observed in the current study, an application of glyphosate between crops is recommended to assist in weed control in a plasticulture system. However, results of this study indicate that an effective replacement for methyl bromide for weed control within the crop has not yet been found.

Many pests were controlled effectively with methyl bromide (nematodes, soil-borne plant pathogenic fungi, soil-borne insects, and weeds), however, the potential

methyl bromide-replacements investigated in this study do not have the broad-spectrum pest control of methyl bromide. Following the elimination of methyl bromide, pest management in vegetable crops will need to further rely on the principles of integrated pest management (IPM). Correct identification of pests and implementation of appropriate control measures have become increasingly important in the effective management of pests in systems that previously relied on methyl bromide. Instead of a limited number of pest control tactics, new pest management systems will need to rely on multiple components aimed at controlling weeds, nematodes, and soilborne plant pathogenic fungi and insects. These systems in the future may also include a broader arsenal of herbicides for several crops with minor hectareage due to the efforts of the US Interregional Research Project 4 (IR-4) (<http://pestdata.ncsu.edu/ir-4/>), which is a collaborative effort between the State Agricultural Experiment Stations and the USDA-Agricultural Research Service. In addition, integration of cultural practices such as crop rotation (McSorley, 1996), pest resistant cultivars (Thies and Fery, 1997), stale seed bed techniques (Johnson and Mullinix, 1998), precision fertilization and watering, the use of organic amendments (Blok et al., 2000; Gardiner et al., 1999; Kirkengaard and Sarwar, 1999) and the choice of polyethylene mulch (Chase et al., 1998; Patterson, 1998) may also improve pest control and should be investigated across multiple disciplines in future studies.

Acknowledgements

This work was supported in part by funds from a competitive grant from the Interregional Research Project 4 (IR-4) and Dow Agrosiences. The authors acknowledge the combined and individual efforts of James Davis, Eddie Sklany, Tommy Hilton, and Jimmy Laska in completing this study.

References

- Becker, J.O., Ohr, H.D., Grech, N.M., McGiffen Jr., M.E., Sims, J.J., 1998. Evaluation of methyl iodide as a soil fumigant in container and small field plot studies. *Pestic. Sci* 52, 58–62.
- Blok, W.J., Lamers, J.G., Termorshuizen, A.J., Bollen, G.J., 2000. Control of soilborne plant pathogens by incorporating fresh organic amendments followed by tarping. *Phytopathology* 90, 253–259.
- Chase, C.A., Sinclair, T.R., Shilling, D.G., Gilreath, J.P., Locascio, S.J., 1998. Light effects on rhizome morphogenesis in nutsedges (*Cyperus* spp.): implications for control by soil solarization. *Weed Sci* 46, 575–580.
- Csinos, A.S., Johnson III, W.C., Johnson, A.W., Sumner, D.R., McPherson, R.M., Gitaitis, R.D., 1997. Alternative fumigants for methyl bromide in tobacco and pepper transplant production. *Crop Prot* 16, 585–594.
- Csinos, A.S., Sumner, D.R., Johnson III, W.C., Johnson, A.W., McPherson, R.M., Dowler, C.C., 2000. Methyl bromide alternatives in

- tobacco, tomato, and pepper transplant production. Crop Prot 19, 39–49.
- Doll, J.D., Piedrahita, W., 1982. Effect of glyphosate on the sprouting of *Cyperus rotundus* L. tubers. Weed Res 22, 123–128.
- Gardiner, J.B., Morra, M.J., Eberlein, C.V., Brown, P.D., Borek, V., 1999. Allelochemicals released in soil following incorporation of rapeseed (*Brassica napus*) green manures. J. Agric Food Chem 47, 3827–3842.
- Hanna, H.Y., Colyer, P.D., Kirkpatrick, T.L., Romaine, D.J., Vernon, P.R., 1994. Feasibility of improving cucumber yield without chemical control in soils susceptible to nematode buildup. HortSci. 29, 1136–1138.
- Jeffers, S.N., Martin, S.B., 1986. Comparison of two media selective for *Phytophthora* and *Pythium* species. Plant Dis 70, 1038–1043.
- Jenkins, W.R., 1964. A rapid centrifugal-flotation technique for separating nematodes from soil. Plant Dis Rep 48, 692.
- Johnson III, W.C., Mullinix Jr., B.G., 1998. Stale seedbed weed control in cucumber. Weed Science 46, 698–702.
- Julian, J.W., Sullivan, G.H., Weller, S.C., 1998. Assessment of potential impacts from the elimination of methyl bromide in the fruit and vegetable trade. Hortsci. 33, 794–797.
- Kirkengaard, J.A., Sarwar, M., 1999. Glucosinolate profiles of Australian canola (*Brassica napus annua* L.) and Indian mustard (*Brassica juncea* L.) cultivars: implications for biofumigation. Aust J Agric Res 50, 315–324.
- Locascio, S.J., Gilreath, J.P., Dickson, D.W., Kucharek, T.A., Jones, J.P., Noling, J.W., 1997. Fumigant alternatives to methyl bromide for polyethylene-mulched tomato. HortSci. 32, 1208–1211.
- Majek, B.A., Neary, P.E., 1991. Selective wavelength transmitting mulch for yellow nutsedge control. Proceedings of the Brighton Crop Protection Conference vol 1, 263–268.
- McSorley, R., 1996. Rotation crops for reducing population levels of root-knot nematodes. Proceedings of the Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. pp. 9.1–9.2.
- Noling, J.W., Gilreath, J.P., 1995. Use of methyl iodide for nematode control. Proceedings of the Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. pp. 49.1–49.3.
- Ohr, H.D., Sims, J.J., Grech, N.M., Becker, J.O., McGiffen Jr., M.E., 1996. Methyl iodide, an ozone-safe alternative to methyl bromide as a soil fumigant. Plant Dis 80, 731–735.
- Papavizas, G.C., 1967. Evaluation of various media and antimicrobial agents for isolation of *Fusarium* from soil. Phytopathology 57, 848–852.
- Patterson, D.T., 1998. Suppression of purple nutsedge (*Cyperus rotundus*) with polyethylene film mulch. Weed Technol 12, 275–280.
- Thies, J.A., Fery, R.L., 1997. Heat stability of root-knot nematode resistance in bell pepper. Proceedings of the Annual International Research Conference on Methyl Bromide Alternatives and Emission Reductions, pp. 32.1–32.2.
- Williams, L.E., Schmitthenner, A.F., 1960. Effect of growing crops and crop residues on soil fungi and seedling blights. Phytopathology 50, 22–25.
- Zhang, W., McGiffen Jr., M.E., Becker, J.O., Ohr, H.D., Sims, J.J., Campbell, S.D., 1998. Effect of soil physical factors on methyl iodide and methyl bromide. Pestic Sci 53, 71–79.